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The Gamma-Ray Continuum Spectrum from the Galactic Center Disk and Point Sources

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ABSTRACT

A light curve of gamma-ray continuum emission from point sources in the galactic center region is generated from balloon and satellite observations made over the past 25 years. The emphasis is on the wide field-of-view instruments which measure the combined flux from all sources within $\sim 20^\circ$ of the center. These data have not been previously used for point-source analyses because of the unknown contribution from diffuse disk emission. In this study, the galactic disk component is estimated from observations made by the GRIS instrument in October 1988. Surprisingly, there are several times during the past 25 years when all gamma-ray sources (at 100 keV) within about 20° of the galactic center are turned off or are in low emission states. This implies that the sources are all variable and few in number. The continuum gamma-ray emission below ~ 150 keV from the black hole candidate 1E1740.7-2942 is seen to turn off in May 1989 on a time scale of less than two weeks, significantly shorter than ever seen before. With the continuum below 150 keV turned off, the spectral shape derived from the HEXAGONE observation on 22 May 1989 is very peculiar with a peak near 200 keV. This source was probably in its normal state for more than half of all observations since the mid 1960's. There are only two observations (in 1977 and 1979) for which the sum flux from the point sources in the region significantly exceeds that from 1E1740.7-2942 in its normal state.

INTRODUCTION

Recent monitoring of the galactic center region by the GRANAT hard X-ray and gamma-ray imaging instruments has shown that almost all gamma-ray sources within a few degrees of the center are variable¹⁻³. These include 1E1740.7-2942, GRS1758-258, and GX1+4. Other observations by imaging and scanning instruments over the past 25 years⁴⁻¹⁷ give occasional snap shots of the point sources in the region. There are additionally more than a dozen observations of the galactic center since 1968 by wide ($>10^\circ$ FWHM) field-of-view instruments. These wide-field measurements can, in principle, be used to determine the sum of the gamma-ray emission from point sources in the region. Efforts to do this in the past¹⁰ were inhibited by an uncertain knowledge of the diffuse continuum gamma-ray emission from the galactic disk. In this paper, we use a recent observation^{18,19} by the balloon-borne Gamma-Ray Imaging Spectrometer (GRIS) to estimate the diffuse continuum component. We then subtract this component from the historical wide-field measurements to obtain the first estimate of the long-term light curve of point-source flux from the galactic center region.

DIFFUSE DISK SPECTRUM

An estimate of the diffuse disk component of the gamma-ray continuum radiation near the galactic center is derived in the paper by Tueller *et al.*¹⁸ in this volume. We summarize the key points and results here. The derivation is based on observations of the galactic center by the GRIS instrument. GRIS is a high resolution spectrometer²⁰ with an array of germanium detectors (1530 cm³ active volume) surrounded by a 15-cm-thick active sodium-iodide shield. The field-of-view is 17° FWHM below 100 keV increasing to ~ 23° FWHM in the MeV range.

Observations²⁰ were made by GRIS on 28 - 29 October 1988 of the galactic center and of a point in the galactic plane 25° west of the center ($l = 335^\circ$, $b = 0^\circ$). The point in the plane was chosen to just exclude the center from the field-of-view. The spectrum at $l = 335^\circ$ is well fit by a broken power law with $F = 9.99 \times 10^{-5} (E/100 \text{ keV})^{-2.64}$ photons cm⁻² s⁻¹ keV⁻¹ below 182 keV and $F = 4.96 \times 10^{-5} (E/100 \text{ keV})^{-1.47}$ photons cm⁻² s⁻¹ keV⁻¹ above 182 keV (see Figure 3 of Tueller *et al.*¹⁸).

We make two key assumptions in this study: 1) GRIS was predominantly measuring the diffuse disk gamma-ray emission in this observation, and 2) this emission has an approximately flat distribution in galactic longitude over the central radian of the disk. With these assumptions the $l = 335^\circ$ GRIS measurement can be used as an estimate of the diffuse disk spectrum at the galactic center. Assumption (1) would be false if point sources near $l = 335^\circ$, $b = 0^\circ$ contribute significantly to the measurement. The only source in the region with a known hard spectrum is GX339-4 in its low X-ray, high gamma-ray state. However, GX339-4 was observed²¹ by Ginga to be in the opposite high X-ray, low gamma-ray state 1.5 months before the GRIS observation. Assumption (1) is therefore probably accurate, although there is some possibility of contamination from GX339-4 (it is a variable source) or other point sources. Assumption (2) would be false if the longitude distribution of the diffuse continuum emission were strongly peaked toward the galactic center. However, the diffuse emission in the 20 keV to 10 MeV energy range is thought to be due to bremsstrahlung of cosmic ray electrons²² and should have a fairly flat distribution over the central radian.

Figure 1 shows the GRIS $l = 335^\circ$ spectrum plotted per radian of the galactic plane and compared with previous observations near the galactic center. If anything, the GRIS spectrum is lower than the others. However, as will be seen in the next sections, there are at least two observations of the galactic center by wide-field instruments that see exactly this same spectrum. The implication is that at these times (23 April 1968 and 22 May 1989) all point sources in the region were in very low-emission states and that the diffuse spectrum estimated from GRIS data is approximately correct for the galactic center region.

ANALYSIS METHOD

The 12 galactic-center observations by wide field-of-view instruments used in this analysis are listed in Table 1. Observations by instruments with fields-of-view greater than 35° were not included due to uncertainties in the disk spectrum beyond the central radian. A few observations by Bell/Sandia and HEAO-1 were not included in this initial study due to the unavailability of detailed spectral data.

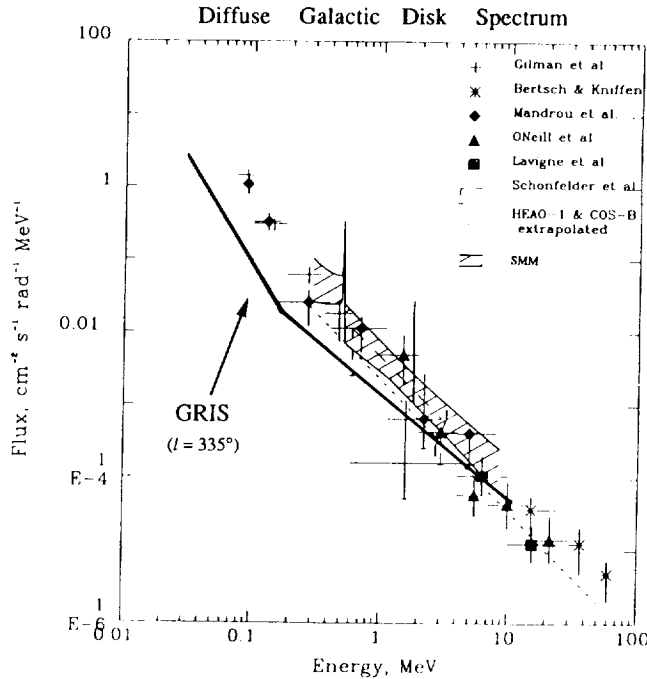


Figure 1 – GRIS spectrum at $l = 335^\circ$ divided by the ~ 0.3 radian GRIS field-of-view, compared with previous measurements of the diffuse gamma-ray emission from the galactic disk near the galactic center. Adapted from Harris *et al.*²³

The procedure used in our analysis was to digitize the published energy spectrum from each observation, subtract off the diffuse component and fit the residual. Examples are shown in Figure 2 for the HEAO-3 observations in 1979 and 1980, where the original and residual spectra are both plotted. The diffuse component was calculated by multiplying the GRIS $l = 335^\circ$ spectrum (per radian of the galactic plane) shown in Figure 1 by the FWHM fields-of-view of the instruments (Table 1). The residuals are estimates of the sum of the spectra of point sources within the fields-of-view. We fit the residual spectra up to ~ 150 keV with a power-law of the form $A (E/100 \text{ keV})^{-\alpha}$. Our emphasis in this initial study is on the hard X-ray spectrum up to 100 keV, so we did not include any data above 200 keV. In this way we also largely avoided contamination from any positronium continuum emission.

RESULTS

Some surprising results are obtained in this analysis. For several of the observations (1968.31, 1974.25, 1980.2, 1989.39) the diffuse component was found to dominate the continuum spectrum. With the diffuse component subtracted off, the residual point-source component is small, and in two cases (1968.31, 1989.39) actually consistent with zero. For example, the HEAO-3 March/April 1980 residual spectrum in Figure 2(b) is seen to be less than one part in ten of the measured spectrum in the hard X-ray band.

The results of the fits (flux at 100 keV, A , and spectral slope, α) to the residual spectra are listed in Table 1 with the flux at 100 keV plotted in Figure 3. Also shown in the figure for comparison is the flux at 100 keV for the source 1E1740.7-2942 in its "normal" state observed by GRIP in 1988¹³ and 1989¹⁴, Mir/HEXE¹⁶ in 1989, and GRANAT/Sigma¹⁻³ in 1990.

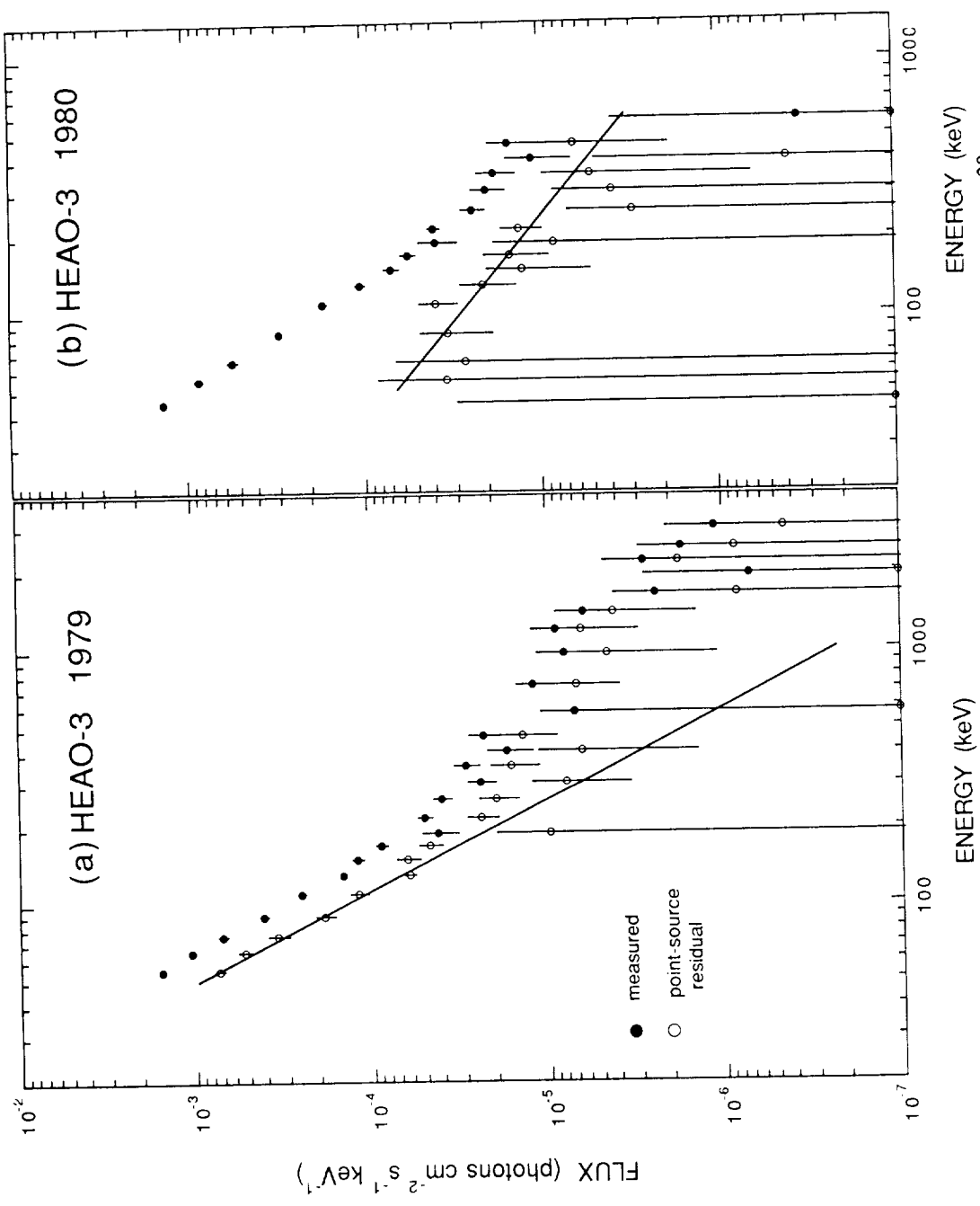


Figure 2 - HEAO-3 galactic center spectrum in (a) September/October 1979 and (b) March/April 1980 as measured³⁰ (filled circles) and with the diffuse disk component subtracted (open circles). The residual spectrum is an estimate of the sum of the point sources in the 30° field-of-view. The best-fit power-law to the residual spectra (lines in figure) in the 50 - 200 keV range is $(1.41 \pm 0.06) \times 10^{-4} (E/100 \text{ keV})^{-(2.8 \pm 0.1)}$ for (a) and $(2.8 \pm 0.6) \times 10^{-5} (E/100 \text{ keV})^{-(1.2 \pm 0.5)}$ for (b).

TABLE 1
Wide-Field Observations of the Galactic Center

Date	Date	Instrument	Field-of-View ^{a)} (FWHM)	Flux at 100 keV, A ^{b)} (10^{-5} photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$)	Power-Law α ^{b)}	Reference
23 Apr 1968	1968.31	Rice Univ.	24°	-2.2 ± 2.4	2.6 ± 3.2	24
25 Nov 1970	1970.90	Rice Univ.	24°	7.1 ± 1.1	2.7 ± 0.4	25
20 Nov 1971	1971.89	Rice Univ.	24°	8.5 ± 1.4	3.5 ± 0.3	26
1-2 Apr 1974	1974.25	Rice Univ.	13°	3.1 ± 0.3	3.0 ± 0.2	27
11-12 Nov 1977	1977.86	Bell/Sandia	15°	18. ± 1.2	2.5 ± 0.3	28
15 Apr 1979	1979.29	Bell/Sandia	15°	9.4 ± 1.9	2.1 ± 0.8	29
Sept/Oct 1979	1979.8	HEAO-3	~30°	14. ± 0.6	2.8 ± 0.1	30
Mar/Apr 1980	1980.2	HEAO-3	~30°	2.8 ± 0.6	1.2 ± 0.5	30
20 Nov 1981	1981.89	Goddard	15°	10. ± 3.3	2.7 ± 1.0	31
1 May 1988	1988.33	GRIS	17°	7.8 ± 1.0	2.8 ± 0.6	18, 19
29 Oct 1988	1988.83	GRIS	17°	11. ± 0.7	2.0 ± 0.1	18, 19
22 May 1989	1989.39	HEXAGONE	19°	0.6 ± 1.0	2.0 ± 2.2	32

a) At 100 keV.

b) Fit to residual point-source flux after diffuse flux is subtracted. Flux = A (E/100 keV)^{- α} .

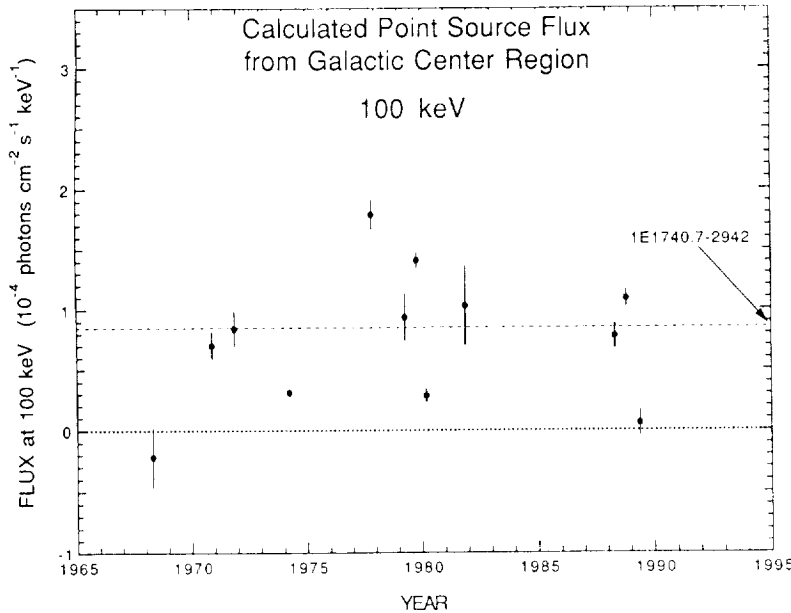


Figure 3 – Residual total point-source flux at 100 keV calculated from wide field-of-view measurements. Fluxes are from Table 1. The 100 keV flux level for 1E1740.7-2942 in March/April 1990¹⁻³ is shown by the dashed line.

DISCUSSION

In terms of point-source emission, the 12 wide-field observations in Figure 3 can be grouped as follows:

- 1) 2 observations (1968.31, 1989.39) are consistent with no point-source emission.
- 2) 2 observations (1974.25, 1980.2) have low point-source emission of $\sim 3 \times 10^{-5}$ photons $\text{cm}^{-2} \text{s}^{-1} \text{keV}^{-1}$. Many sources are candidates for this emission. The flux level is about right for GRS1758-258 as observed³ in March/April 1990, 1E1740.7-2942 in its low state as observed¹ in February 1991 or GX1+4 as observed³³ in the 1970's.
- 3) 6 observations (1970.90, 1971.89, 1979.29, 1981.89, 1988.33, 1988.83) have 100 keV flux levels consistent with that of 1E1740.7-2942 in its normal state, although significant contributions from other sources such as GX1+4 and GRS1758-258 can not be ruled out. The 1988.33 observation by GRIS was just 18 days after an observation by GRIP in which 1E1740.7-2942 was indeed found to be in its normal state and the only strong 100 keV source in the region.
- 4) 2 observations (1977.86, 1979.8) have flux levels significantly exceeding that of 1E1740.7-2942 in its normal state. The 1977.86 observation by Bell/Sandia was just 12 days before an observation³⁴ by the NRL high-energy X-ray balloon instrument, which scanned the galactic center region. The scans revealed comparable 100 keV fluxes from 1742-294, which is very likely the same source as 1E1740.7-2942, and from 1743-322.

We thus conclude that there are few strong point sources of 100 keV emission within $\sim 20^\circ$ of the galactic center and that all of them are variable. The black hole candidate 1E1740.7-2942 is probably a dominant contributor to the high energy flux for more than half of the observations.

1E1740.7-2942 Turn-Off

There are 5 observations of 1E1740.7-2942 within a period of two months in March-May 1989. Two are with imaging instruments (GRIP¹⁴, EXITE¹⁷), two with narrow ($< 2^\circ$) field-of-view instruments (Mir/HEXE¹⁶, POKER¹⁵) and one with the wide-field HEXAGONE³² (Table 1). A plot of the 1E1740.7-2942 60 keV flux as a function of time from these observations is shown in Figure 4. The HEXAGONE data point is the residual after the diffuse disk flux was subtracted and represents an upper limit for any point source in the field-of-view. The source turned off in gamma-ray continuum emission in 13 days. This is the fastest variability ever seen in 1E1740.7-2942 and implies a compact emission region of size less than 13 light days.

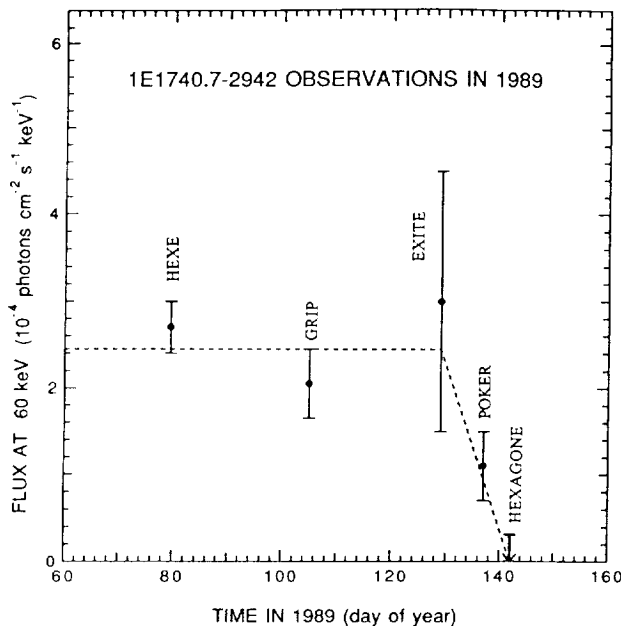


Figure 4 – The flux at 60 keV from 1E1740.7-2942 vs. time for observations between 20 March and 22 May 1989 by Mir/HEXE¹⁶, GRIP¹⁴, EXITE¹⁷, POKER¹⁵ and HEXAGONE³². The HEXAGONE point is a 1σ upper limit for all sources in the $\sim 19^\circ$ field-of-view. The source turn-off occurs in 13 days. Note that in order to have best statistics for all measurements, this plot is at 60 keV instead of the 100 keV used elsewhere.

170 keV Feature

The 130-180 keV feature observed³² in the 22 May 1989 HEXAGONE spectrum of the galactic center becomes more prominent when the diffuse disk emission is subtracted, as shown in Figure 5. The point-source spectrum actually has a maximum at ~ 170 keV. This feature has been interpreted³⁵ as a Compton backscatter peak from an accretion disk or cloud surrounding a source of 511 keV positron annihilation photons. Figure 5 shows that on 22 May 1989, the only significant gamma-ray emission from the galactic center region was in two lines (170 and 511 keV) both probably associated with positron annihilation.

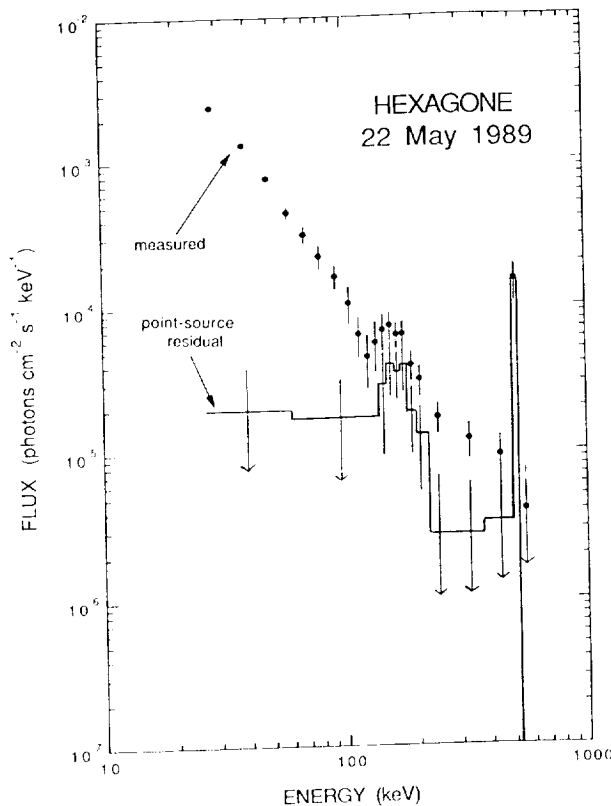


Figure 5 – HEXAGONE galactic center spectrum on 22 May 1989 as measured³² (filled circles) and with the diffuse disk component subtracted (histogram). The data points below 130 keV for the residual spectrum have been averaged to improve statistics.

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